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Simulating Earthquake Damage to the Electric-Power Infrastructure: A Case Study for Urban Planning and Policy Development

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Statement of Scope and Purpose

The authors present a case study of the evaluation of consequences of a moderate earthquake in the Los Angeles basin to the electric-power infrastructure of the western United States. This infrastructure consists of long, high-voltage transmission lines that bring electrical power from remote generating stations to population centers. This transmission infrastructure is vulnerable to damage from natural disasters such as earthquakes. This paper presents a multidisciplinary approach to earthquake-consequence assessment combining computational models from seismology, probabilistic risk assessment, and electrical engineering to provide input for urban-planning and policy-development applications.

Abstract

This paper presents a case study of the consequences of a magnitude 6.75 earthquake on the Los Angeles Elysian Park fault to the electric-power infrastructure of the western United States. The analysis combines aspects of geological modeling of such an earthquake with probabilistic simulation of power-system component failures for evaluation of the operation of the engineering infrastructure. This hybrid analysis demonstrates emergent behavior of a complex system and illustrates the challenges of multi-disciplinary analyses necessary for computation operations research. The simulation predicts blackouts in the Los Angeles metropolitan area and abnormal voltages throughout the western U.S. electric-power infrastructure that reflect the consequences observed following a recent Northridge earthquake. The paper discusses applications of such analyses for urban planning and policy development.

Keywords

simulation, earthquake modeling, electric-power infrastructure

1. Introduction

Recent attention has been given to the problem of assuring the security of our urban and national infrastructures. This year also brings to an end the International Decade for Natural Disaster Reduction (IDNDR). This decade has seen substantial attention on the awareness of problems related to natural hazards and how such hazards pose a major threat around the world. One big drawback of the IDNDR in the earlier part of the decade was its lack of focus on problems of disasters in large cities. The United Nations estimates that by the year 2025, 61% of the world's population will be living in cities and there will be 28 "giant metropolitan complexes" of over 8 million people [1]. A study by Degg [2] shows that about 78% of the world's 100 most populous cities are exposed to at least one of the following hazards: earthquakes, tsunamis, volcanoes, and windstorm. About 45% are exposed to more than one of the above hazard types.

Disasters in large cities pose an enormous risk not only to the city itself, but to the hinterland and national economy of the country as well. Recognizing this threat of natural hazards on large urban agglomerations, the latter half of the decade has seen projects such as RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas Against Seismic Disasters) [3], Earthquake and Megacities Initiative sponsored by the IDNDR [4], and other initiatives such as the Urban Security Initiative [5]. Such projects aim to highlight the problems of disasters in large cities and to understand various ways of addressing the problems. The high population density, complex societal mix, large income gap, abject poverty, and a large informal sector associated with most large cities, lead to a complex

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intermingling of cause and effect which is only compounded by the increased reliance on technological systems for normal functioning. Thus recovery is slow in most cities owing to the greater vulnerability of infrastructure networks or what may be termed the lifelines of the city [6]. The concentrated but distributed functionalities such as food, power, transportation, etc. all depend on high-tech infrastructure that breaks down at the time of a disaster and paralyzes the city. An important aspect of addressing the problems of disasters in large cities is to understand better the performance of the various urban systems such as transportation, electrical generation-and-distribution, housing, water supply, and so on and the inter-linkages between them [7]. Thus, the focus should be on integrated modeling, combining models from various disciplines to have a comprehensive analysis of the situation.

This paper summarizes a research effort at the Los Alamos National Laboratory (LANL) assessing the potential impact to the national electric-power infrastructure from earthquakes. It presents a context for this work, discusses geological and engineering aspects of the problem, and presents results of a simulation of a moderate earthquake on Los Angeles' Elysian Park fault and the possible consequences of such an event. Finally, this paper discusses operations-research applications of the work for urban planning and disaster mitigation.

2. Research Context

Urban infrastructure systems such as transportation, communication, electric power and energy, water and sewage system, etc. form the lifelines of the urban organism. For a proper functioning of the urban system, each of these networks has to be robust. The electric-power network is particularly important as almost all modern-day urban activities rely on it for proper functioning. The need for electricity requires no major discussion. It is well known to everyone that electricity is important not only for lighting, heating, ventilation, air conditioning, operating various appliances, etc. but also for emergency communication, vehicular and air traffic control, and all control systems in command and control operations and also in commercial and industrial operations. Thus the loss of electricity due to earthquakes can cost billions of dollars to the national economy. The electrical network is also particularly vulnerable to earthquake damage as can be seen in the recent breakdown in power from earthquakes in Loma Prieta, Northridge, etc.

Damage to the electrical network due to an earthquake is not restricted to the geographical location of the earthquake alone but has far-reaching implications for other regions as well. For example, the damage of electrical network components in Los Angeles due to the Northridge Earthquake caused power outages as far away as British Columbia, Montana, Wyoming, Idaho, Oregon, and Washington (the longest one lasting 3 hours in Southern Idaho) [8]. This can either be due to first-order direct damage to the generating stations, substations, or transmission and distribution networks, or alternatively due to second-order indirect damage caused by the change in load due to consumer demand, etc. Therefore, electrical networks need to be assessed in terms of their vulnerability to damage from natural hazards. This assessment must include not simply the assessment of vulnerability to all components of the network, but rather an assessment of the system as a whole. This is of utmost importance in understanding how, for example, an earthquake in Los Angeles will affect regions far beyond the Los Angeles metropolitan area. To understand the system performance of the electrical network due to a scenario earthquake, there are three important models that need to be integrated –

1) Generation of best-possible ground-motion parameters (peak ground acceleration, peak ground displacement, or response spectrum) for the scenario earthquake.

2) Combining the ground motions with component fragility to compute the damage state for each of the power system's components.

3) Using the damage-state probabilities to undertake systems-engineering analysis to assess the performance of the electrical system.

Although each of the above models has been developed and used singularly, the need to integrate these models is crucial to any kind of damage assessment. The integration of models also involves the exchange of input and output values from one model to another in a way that the results of one model can be used by another. The objective of this paper is to understand this integrated approach to modeling and to demonstrate the results of a test of this approach in the context of a large earthquake of magnitude 6.75 on the Richter scale on the Elysian Park fault under downtown Los Angeles. The paper will discuss the existing methods, problems related to data, and new methods used in each of the above models for this paper. Finally, the paper will provide results of the tests of the above approach for the City of Los Angeles and discuss briefly the policy implications of such modeling and how results of such integrated models can be useful to decision makers.

3. Earthquake / Infrastructure Simulation

3.1 Modeling Scenario Earthquake Ground Motions

One of the most important aspects of understanding the effects of earthquakes is to predict the resultant ground motions due to a certain earthquake with a high degree of reliability. The distribution of ground motion in real earthquakes is often very non-uniform and consequently the distribution of damage is also non-uniform. This could be seen in the Loma Prieta earthquake in California and again in the Northridge earthquake in Los Angeles. The three-dimensional nature of the velocity structure in deep sedimentary basins makes it very difficult to predict the ground motions in Los Angeles [9]. Most ground motion studies have been limited to one-dimensional velocity model using the method of propagating ruptures on a finite fault, that do no incorporate the effects of basin structure. More recently efforts have been made to develop more complicated 2D or 3D velocity structures. Although most such efforts limit the earthquake source to be a point source or a plane wave, some recent efforts include the modeling of a 3D velocity structure and a propagating rupture on a finite fault area [9]. This method developed by Olsen and Archuleta [9] has been used in this study. It utilizes first principle simulations of the earthquake ground motions and takes into account subsurface geology, particularly in basin settings. It also includes the important effects of surface sediments. Although most studies so far are limited to low frequencies (less than or equal to 1 Hz), due to extensive computational requirements, the ground motions used in this study incorporate high frequencies (of 3 Hz). This was considered essential because ground motions with significant energy content at frequencies of 3 Hz and greater largely cause damage to the components of the various urban infrastructure systems. The finite area that was modeled using this method incorporated a grid mesh of 75 x 75 at regular spacing 2 km apart, covering the Greater Los Angeles area.

The method was validated against the Northridge earthquake and the results obtained were close to the real ground motions observed in the Northridge earthquake, as can be seen in Figure 1. Furthermore, the ground motions developed thus were considered much more satisfactory when compared to the ground motions generated by commonly used earthquake damage estimation models such as HAZUS™ [10] as shown in Figure 2. The event used for this simulation is an event of magnitude 6.75 on the Richter scale on the Elysian Park fault, which runs under downtown Los Angeles. The Elysian Park fault is a member of the Los Angeles Fault System [9], whose collective average recurrence interval for an M 7.2 to 7.5 earthquake is similar to that of a similar magnitude earthquake on the San Andreas fault necessitating equal attention to these individual faults. Furthermore, an earthquake on this fault can be quite disastrous to the City of Los Angeles as it is underneath a downtown populated with dense and compact high-rises, thereby increasing the exposure of wealth and population. Also, such an earthquake is likely to cause significant direct damage to the substations located in the region as well as remove a significant amount of load that will affect large areas well beyond the geography of Los Angeles. The ground motions (peak ground acceleration) for such a scenario earthquake are shown in Figure 3.

3.2 Electrical Network Component Fragility

Fragility curves are used to estimate the probability of a certain level of damage to the equipment based on ground motion parameters at the site of the equipment. These curves are developed from data from past earthquakes to determine the probability that a certain level of damage is likely to occur to a certain type of equipment/structure based on the ground motions experienced at the site. An example of a fragility curve is shown in Figure 4. Each fragility curve is characterized by median and lognormal standard deviation values of the ground-motion parameter. For the analysis of electrical systems, the ground-motion parameter that is frequently used is peak ground acceleration. The Utilities Working Group (UWG), a group of experts from several utilities from California that convened in 1993 to assess the quality of earthquake damage data, developed standardized classification of equipment. For each of the equipment classes, experts defined failure modes and developed opinion-based fragility curves [11]. Other studies are being done to compare these fragility curves with real damage data to analyze the validity of the opinion-based fragility curves [11]. However, the development of fragility curves based on damage data alone is difficult as most often damage data are insufficient to adequately define a fragility curve. Other methods such as HAZUS™ use fragility curves based on a combination of expert-based fragility curves and damage data from various earthquakes [10]. Even though this method has its limitations, it was considered appropriate for use in this research.

For electrical substations and networks, the HAZUS™ [10] method classifies electrical network components in three broad classifications – substations, distribution circuits, and generation plants. Each one is further subdivided into many classes depending upon various criteria such as high-, medium-, and low-voltage substations with anchored and unanchored components (Table 1). For each of these classifications, fragility curves are developed based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents [10]. For example, for a substation to be in the extensive damage state, there should be failure of 70% of its disconnect switches, 70% of its circuit breakers, 70% of its current transformers, or 70% of its transformers. Each of the different damage states are described in detail in Table 2.

The data on electrical substations and generation plants were compiled as described in the section below, converted into a format required by HAZUS™ (FEMA 1997), and input into it. The results obtained from this model were damage-state probabilities of each of the substation and generation equipment. These probabilities were converted into an absolute damage state using Monte Carlo methods to be utilized in the engineering analysis as described below.

3.3 Engineering Analysis

The electric-power infrastructure (EPI) is a collection of generating plants that produce electrical energy by converting other energy resources, a network of high-voltage transmission lines that convey electricity from the generating plants to substations where the voltage is lowered by transformers, and a subordinate collection of radial distribution networks that deliver low-voltage electric power to end-use consumers [12]. The U.S. EPI contains generating plants that harness coal, natural-gas, nuclear, and hydro resources, as well as other energy resources including wind, solar radiation, and waste heat from industrial processes. The U.S. EPI's high-voltage transmission system is divided into several standard nominal voltages, primarily 765, 500, 345, 230, 161, 138, and 115 kV. Higher-voltage transmission lines require less current per unit of power transmitted, thus lowering resistive transmission losses and improving efficiency. Transformers couple the voltage layers. Transformers are sets of coils magnetically coupled by iron cores. The turns ratios of the coupled coils automatically convert the alternating current between voltage layers, and these turns ratios can be controlled (within limits) to adjust the voltages at substations to the desired nominal values. Transformers also lower the voltages to practical levels for use by consumers.

The EPI of the continental U.S. is divided electrically into four interconnections – Western Systems Coordinating Council, the Eastern Interconnection, the Electric Reliability Council of Texas, and Hydro Quebec. Within each of the four interconnections, the sinusoidal frequency is controlled to a nominal 60 Hz. All generating units within an interconnection produce electricity with the same frequency, regulated to within 0.00014 Hz average error each hour [13]. The stability of the control of these generating units' speeds is an important reason for the partitioning of the EPI into independent interconnections. The AC transmission systems of the four interconnections are connected by a small number of AC-DC-AC converter stations that provided limited power transmission between the interconnections.

The interconnection containing Los Angeles is the Western Systems Coordinating Council (WSCC). WSCC serves the western United States, western Canada, and a small portion of the Mexican states of Sonora and Baja California. In 1997, WSCC included 157,783 MW of generating capacity, served 65 million people across 1.8 million square miles, and contained 107 commercial utilities and independent power producers [14]. The WSCC EPI contained a transmission system with 89,077 miles of high-voltage transmission lines. It also contained three high-voltage DC transmission lines [15]. These unusual components are useful for transmitting large amounts of power long distances. Two of the DC lines traverse California, bringing power to northern Los Angeles from the Oregon border. The third DC line crosses Nevada, bringing power to northeastern Los Angeles from west central Utah.

The importance of Los Angeles as a center for electricity utilization in WSCC should be emphasized. Data from the California Independent System Operator (CaISO) predicted a coincidental 1999 summer peak load for WSCC of 127,700 MW. Two utilities, the Los Angeles Department of Water and Power (LADWP) and Southern California Edison, serve Los Angeles and the surrounding urban and suburban region. These two utilities comprise 23,250 MW (18.2%) of the CaISO summer-peak-load data.

Traditional analyses of electric-power transmission systems emphasize calculations of the flow of power through a network of transmission lines [16]. Each node in the transmission network is characterized by two parameters of a phasor voltage, the magnitude and relative phase angle of this voltage. Each transmission line can be described by a pi-network equivalent, consisting of a series resistance and inductive reactance between the endpoints of the line, with a shunt charging capacitance between each of the endpoints and ground. This characterization leads to a large system of nonlinear equations. In 1967, Tinney and Hart [17] proposed a technique for the efficient solution of this system of equations, and their technique is still used in commercial engineering software. In most transmission lines the line impedance is dominated by the series inductive reactance, and this characteristic can be used to linearize the system of equations for an efficient approximate solution [18]. Power-flow analyses for this study used a nonlinear solution code developed by the University of Texas at Arlington's Energy Systems Research Center.

3.3.1 Data Requirements

The power-flow calculations require specification of engineering parameters for individual substation-bus, transmission-line, and generating-unit components. Generating-unit data include the scheduled real-power output from the generator, the maximum and minimum reactive-power limits for this scheduled real power for voltage control, and the desired generator-bus voltage for adjustment of reactive-power generation. Transmission-line data include the two substation buses linked by the line, the pi-network impedance (series resistance, series reactance, and shunt capacitance), and MVA power-flow capacity. If the line is a transformer, then the voltage-adjustment tap setting and any phase-angle regulation are also required. Substation-bus data include the aggregate real and reactive power for the consumers served from the bus, and any shunt compensation used for voltage control.

EPI data for this study came from several sources. The CaISO provided engineering data for this study. The CaISO summer coincidental peak-load database includes data for 9999 substation buses and 12727 transmission lines, representing all of WSCC. These data include all parameters necessary for power-flow calculation, including a consumer-load forecast and a schedule of generating-unit commitment. The California Energy Commission and the Federal Energy Regulatory Commission provided transmission-system maps of California and Los Angeles.

3.3.2 Integration Challenges

Coupling analyses of the geology of ground motions of earthquakes and consequential analyses of probabilistic failures of infrastructure components with the engineering analyses of the power flow through the EPI presents several novel challenges. One of the most interesting of these challenges is the identification of geographical areas served by the (radial) distribution systems emanating from EPI transmission substations. Individual substations serve a distribution network that provides electric power to consumers in a specific geographic area. This area is called the substation's service area. Although this area is known precisely to the utility that owns the substation, the area is not documented by public regulatory agencies. Ergo, the area must be estimated by non-utility organizations performing geographic-based (e.g., urban-planning) studies. This problem has been examined previously using Voronoi estimation techniques [19], but that approach has deficiencies in ability to use population-density and land-use data to improve service-area estimates or to avoid water and rough-terrain obstacles that present service-area constraints. Los Alamos National Laboratory (LANL) has explored a cellular-automata service-area estimation technique for improved use of geographic data [20] and with application to load-forecasting using synthetic-population methods [21].

Another important challenge is the coupling of the probabilistic failure states of substations computed by HAZUS™ to a scenario of failures specific to discrete components represented in the EPI database. A direct method for a measurement of component failures is the Monte Carlo technique. Using a good random number generator [22], a failure state for each component is selected from the range of failure states using the HAZUS™ failure-state probabilities as a mathematical mapping function. Then the component failures are reported to the EPI database for subsequent evaluation of consequences to power flow through the components that survived the earthquake. This Monte Carlo procedure can be repeated to generate a probabilistic prediction of EPI transmission or voltage problems, or the similar likelihood of blackout for specific geographic locations.

A significant uncertainty in the assessment of post-earthquake consequences of EPI power-flow conditions is the range of human and machine events that will occur following a stress to the EPI. Specifically, the greater loss of load relative to loss of generation capacity anticipated from an earthquake in the Los Angeles area will leave WSCC with a surplus of scheduled generation. To control voltages and to maintain 60-Hz system frequency, automatic and manual choices will be made to turn off generation across WSCC. These choices involve decisions by human operators at utility and independent-system-operator control centers, and the range of choices makes prediction of the decisions difficult. Even the actions of the automatic generation control systems are difficult to predict, owing the proprietary nature of these control systems, the variations in policies for load shedding and voltage control among the several utilities of the WSCC, and the complex and temporally-dependent nature of these systems.

Finally, an objective of the analyses of the implications of earthquakes to the EPI is the evaluation of policies for urban planning, infrastructure development, resource allocation, and infrastructure restoration. However, the output from the EPI engineering analyses is a prediction of the electrical state of the various EPI components. Coupling these engineering analyses with policy decisions is an important challenge. Although outwardly unrelated, EPI calculations can reveal information useful for selecting policies. Specifically, the identification of likely infrastructure failures is useful for determining the type and quantity of spare parts needed for infrastructure restoration. The expected quantity and cost of these spare parts, and decisions about desirable locations for their storage, can be determined from analyses of EPI damage from earthquakes. Likewise, such analysis can assist in planning for emergency generators in essential facilities in areas that are likely to have blackouts. Such analysis can help decision makers to decide where emergency generators or other power supply is needed and for how long. Furthermore, by running this analysis for many different scenarios, one can analyze the pattern of damage, study which substations are likely to get damaged under many scenarios, and prioritize the mitigation and restoration strategies for each of the substations.

3.3.3 Simulation Methods

The procedure for EPI analyses in this study is to couple the results of the HAZUS™ analyses to the EPI database, perform base-case and post-earthquake power-flow studies, and present the results in GIS and tabular formats.

A damage scenario is produced from the HAZUS™ results by selecting a damage state for each EPI substation using a Monte Carlo technique. The HAZUS™ results report the percentile probability that the damage state will be no damage, slight damage, moderate damage, extensive damage, or complete damage. The percentages for each state comprise a partition of the real-number space between 0 and 1. A random number [22] between 0 and 1 selects a state for each substation from the possibilities, and this state is used for the subsequent EPI analyses. With no damage, no modification is made to the substation in the EPI database. For complete damage, the substation is removed from the database, and any generating units or transmission lines connecting to this substation become disconnected and so are removed from the database. Similarly, extensive damage (independent 70% probability of failure of each circuit breaker, switchgear, bus component, transformer, etc.), results in a likelihood of less than 0.07% that each transmission circuit terminating at the substation will remain operable. Substations having extensive damage were removed from the database, along with the incident generating units and transmission lines. For substations with slight or moderate damage, the substation was left in service in the database, with a reduction in the aggregate consumer load resulting from probable failures of portions of the substation's distribution apparatus.

The EPI analyses determine the power flow through each transmission line and the voltage at each substation node. An analysis was performed for the base case (pre-earthquake condition under the assumptions of the CaISO data set) and for post-earthquake conditions for a single Monte Carlo scenario sampled from the HAZUS™ analysis of an Elysian Park earthquake. Differences between the results of these two analyses indicate consequences of the earthquake.

GIS presentation of the results was made possible by geographic information obtained from maps from the California Energy Commission and the Federal Energy Regulatory Commission. These maps were scanned and registered for display by commercial GIS software, with overlays digitized from the maps to indicate the locations of EPI components found in the CaISO database. The digitized GIS objects allow a graphical presentation of the results of the EPI analyses.

The digitized substation locations were superimposed on a GIS database of Anderson land-use codes for geographic subregions throughout the Los Angeles study area. Our cellular-automata software that estimates the service areas of each substation in the study area processed this graphical presentation. The resulting bitmap image allowed additional graphical presentation of the consequences of the earthquake.

4. Simulation Results

Figure 5 shows the estimated service areas of substations in the Los Angeles study area. Each area represents geographically the set of consumers expected to be served by each of the substations. Some remote agricultural and forest terrain northeast of Los Angeles was excluded from the estimate owing the large uncertainty in the identification of the substation(s) serving this region. Because of the small consumer load of this region, impact of this uncertainty to our analyses was insignificant.

Table 3 shows the results of the HAZUS™ damage-state probability calculation and the result of a single Monte Carlo sample of damage states for representative substations in the study area. Substation damage ranged from none to complete. As can be expected from Monte Carlo simulation, some low-probability results were selected. The HAZUS™ results found 43 substations with a probability of extreme or complete damage exceeding 50%. These substations and substations and their Monte Carlo-selected scenario damage states are listed in Table 4.

Figure 6 shows the Monte Carlo-selected scenario damage states for each substation in the Los Angeles study area. Note the geographic correlation between the substations experiencing complete failure with the location of the Elysian Park fault.

Figure 7 shows areas of Los Angeles where blackout occurs from consequences of the earthquake. This figure shows areas where blackout occurs either from first-order isolation resulting from the failure of a substation cutting off the flow of power to the distribution system, or from second-order isolation by substation failures removing all transmission paths to substations downstream. Blackout will occur at substations experiencing second-order isolation because no transmission circuits remain to bring power to these substations, even though no earthquake damage occurred at the substation. Using data from the CaISO 1999 summer-peak-load database, the first- and second-order isolation removes 11,448 MW of consumers' loads and 4,400 MW of scheduled generation from the EPI. The load removed by the Elysian Park earthquake scenario is 8.9% of the entire WSCC EPI load. The removed scheduled generation is 3.3% of the entire WSCC EPI generation. These perturbations leave WSCC with a significant excess of scheduled generation. This excess generation will produce higher-than-nominal voltages and increased system frequency. Manual and automatic generation control must reduce the generation to match the post-earthquake load to prevent these voltage and frequency problems.

As an academic assumption, we reduced the surviving scheduled generation uniformly (to 95% of the scheduled value) across WSCC. This reduction in generation matched closely the post-earthquake demand (plus transmission losses resulting from the new generation schedule). The consequent power flow revealed surprisingly few problems for the WSCC EPI. Two types of problems occur. First, power flow is shifted by the line failures and changed load and generation schedules, producing thermal overloads (flows that exceed the thermal capacities of transmission lines). Overloads that occur are small (a few tens of megawatts on only eight transmission lines) and could be mitigated by changing the post-earthquake generation schedule. Second, the failures produce changes in reactive power flow that lead to non-nominal voltages at substations. These problems are more serious. There are 129 substations with voltages 10% or more above normal, and one substation with voltage 20% above normal. These are large excursions from the normal voltages, and could exceed the capability of the voltage-control apparatus to mitigate these abnormal voltages. These abnormal voltages occurred throughout WSCC. Table 5 lists the number of substations having abnormal voltages in each of the WSCC control-area subsystems, and Figure 8 shows the locations of these substations. Several of these substations' abnormal voltages are serious problems, particularly those at substations of the high-voltage backbone through northern California, Washington, and Oregon. Abnormal voltages occur at the Malin, Captain Jack, and Grizzly substations in Oregon; Hanford, Ashe, Lower Monumental, Little Goose, and Lower Granite substations in Washington; Round Mountain and Olinda substations in California; and at substations as far away as Colorado and British Colombia. More information is necessary to predict how the WSCC EPI's relays and other devices would respond to these abnormal voltages, to determine if there could be cascading failures that would result in blackouts of areas far removed from Los Angeles for this Elysian Park earthquake.

5. Future Research

Several things could improve this EPI analysis of the consequences of an Elysian Park earthquake. First, the HAZUS™ failure probabilities are assumed to be independent in the Monte Carlo scenario realization. In the Monte Carlo simulation, it is possible for adjacent buses at the same substation to experience radically different failure states. Modification of the HAZUS™ results to produce conditional probabilities for correlated failures at substations could reduce this effect. Also, the HAZUS™ results are aggregate for entire substations, but must be decomposed to produce failure states for individual substation buses and transmission-line switchgear. Modifying HAZUS™ to produce failure states for each of the components specific to the CaISO database would improve this facet of the analysis. Further, fragilities for transmission lines could produce HAZUS™ failure probabilities for those circuits that traverse the earthquake area with towers and other apparatus that could be affected by ground motion. Circuit routes could be determined from California Energy Commission maps to use such fragility data.

Second, the generation rescheduling determined to be necessary following an Elysian Park earthquake will require human decisions. The specific decisions about which generators to ramp down or turn off will affect the resulting power flow. Better representation of these human decisions would improve the simulation and analysis.

Third, the EPI analyses that can be performed evaluate pre- and post-earthquake steady-state conditions. However, the temporal aspect of the infrastructure during the failures is important. Voltage transients will occur as substations fail, generators become isolated, and circuit breakers disconnect transmission lines. The specific times of these events cannot be forecast, but the important transient EPI phenomena depend upon these times. Similarly, additional data are necessary to model the high-frequency behavior of generating units and control devices during transients, but these data are unavailable. Although transient phenomena are important during EPI catastrophes, they are difficult or impossible to model.

Fourth, the EPI analyses for this study used the assumptions of the CaISO summer-peak-load forecast for WSCC. The pre- and post-earthquake conditions depend on the load and generation schedules from this assumption.

The analyses could be improved by using the population and land-use databases in conjunction with the estimated substation service areas to predict off-peak loads to assess the consequences of Elysian Park earthquakes at arbitrary times.

Finally, this study reports the results of a single Monte Carlo realization of a scenario of failure states following an Elysian Park earthquake. Much information could be obtained from statistics of results from multiple scenarios.

6. Applications to Urban Planning

The results of analyses of earthquake implications to the electric-power infrastructure can provide information valuable for urban planning and disaster mitigation. Ideally, the data produced could be used to improve the design of the infrastructure, by changing the routing of certain transmission corridors into affected neighborhoods to reduce the likelihood that all transmission paths would be damaged by the disaster. However, the cost and social barriers to such major construction of overhead transmission lines are likely to preclude such measures. Instead, the data can be used to site replacement equipment and supplies, to forecast the extent of blackout areas and their consequences, and to plan restoration procedures.

Repair and replacement of damaged apparatus is essential to the restoration of power following an earthquake-induced blackout. The HAZUS fragility data indicate the possibility of damage to transmission-line towers; substations' circuit breakers, transformers, and switchgear; and communications apparatus. Certainly, preparing a stock of repair and replacement parts for this equipment is important. Also important is the standardization (to the extent possible) of this equipment, so that the repair and replacement parts will avail the most general application. The forecast of damage from the simulation can be used to determine what types and how many of the spare parts should be stocked. A final consideration is the location of these parts, in areas that are possibly sheltered from potential damage, in means that further protect these parts from damage, and in physical locations that will be accessible to repair crews, proximal to locations where damage is likely, and where transportation infrastructure surviving the earthquake will be available for the transport of these parts to where they are needed.

The forecast of the blackout area is an important result of the simulation. These data can be used to determine the consequences of the earthquake to the services that depend on electric power. Such services include medical facilities, food storage, and communications. The data can be used by disaster-relief agencies to determine the number of persons likely to be affected, the quantities of survival and medical supplies needed, and the duration for which important services may be affected.

A final application of the forecast of the blackout area is the development of plans to restore power. Prioritization of the repair of transmission routes bringing power into the affected neighborhoods is possible. By concentrating restoration efforts on the minimal critical transmission paths needed to bring restore power to the affected neighborhoods, the duration of the blackout can be reduced.

Although it is likely impossible to design the electric-power infrastructure so that it is invulnerable to damage from earthquakes, integrated analyses of earthquake ground motions and their consequences to infrastructure operation can mitigate these consequences. As the urban populations in locations vulnerable to natural disasters continue to grow, awareness and preparedness will become increasingly important to limit the consequences of these disasters to human life and welfare.

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Figure Captions

1. The earthquake model used in this paper compares favorably with earthquake measurements. Here are the modeled peak ground accelerations (left) and measurements (right) for the recent Northridge earthquake. The model was accurate in both the magnitude and geographic extent for this event.

2. A HAZUS™ model (left) of the recent Northridge earthquake underestimated the peak ground acceleration and overestimated the geographic extent of the event. This figures compares this model with the measurements (right).

3. The model used in this paper predicts peak ground accelerations as high as 1.02 g for a 6.75-magnitude Elysian Park earthquake. This is the scenario explored in this paper.

4. Component fragility curves show the probability of various damage states for an electric-power substation as functions of peak ground acceleration during an earthquake.

5. A cellular-automata technique used land-use data and electric-power substation locations to estimate substations' service areas.

6. Damage states for substations affected by the earthquake were simulated with Monte Carlo techniques using the component fragility curves and the predicted peak ground accelerations. This result for a single iteration of the Monte Carlo simulation shows the correlation of expected substation failure with proximity to the Elysian Park fault.

7. Substation failures can cause blackouts in their service areas, and can cause blackouts in the service areas of neighboring substations that become isolated by other failures that cut off paths of power flow through the transmission grid.

8. The modeled Elysian Park scenario produced abnormal voltages at substations throughout WSCC. This phenomenon also was observed following the recent Northridge earthquake.

Table 1
Classification of Electrical Network Components as used by HAZUS™ Source: HAZUS™ (FEMA 1997)

Name	Description
	Transmission Substations
ESS1	Low-Voltage (less than or equal to 115 kV) Substation with Anchored Components
ESS2	Low-Voltage (less than or equal to 115 kV) Substation with Unanchored Components
ESS3	Medium-Voltage (115 kV - 230 kV) Substation with Anchored Components
ESS4	Medium-Voltage (115 kV - 230 kV) Substation with Unanchored Components
ESS5	High-Voltage (230 kV - 500 kV) Substation with Anchored Components
ESS6	High-Voltage (230 kV - 500 kV) Substation with Unanchored Components
	Distribution Circuits
EDC1	Distribution Circuits with Seismically Designed Components
EDC2	Distribution Circuits with Standard Components
	Generation Plants
EPP1	Small Power Plants with Anchored Components < 100 MW
EPP2	Small Power Plants with Unanchored Components < 100 MW
EPP3	Medium/Large Power Plants with Anchored Components ≥ 100 MW
EPP4	Medium/Large Power Plants with Unanchored Components ≥ 100 MW

Table 2
Description of Various Damage States for Electrical Network Components (Source: HAZUS™, FEMA 1997)

Damage State Description	**Substations**	**Distribution Circuits**	**Generation Plants**
Slight/Minor	Failure of 5% of the disconnect switches, 5% of circuit breakers, or by building being in minor damage state	Failure of 4% of all circuits	Turbine tripping, light damage to diesel generator, or building being in minor damage state
Moderate	Failure of 40% of disconnect switches, 40% of circuit breakers, 40% of current transformers, or building being in moderate damage state	Failure of 12% of all circuits	Chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or building being in moderate damage state
Extensive	Failure of 70% of disconnect switches, 70% of circuit breakers, 70% of current transformers, 70% of transformers, or building being in extensive damage state	Failure of 50% of all circuits	Considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or building being in extensive damage state
Complete	Failure of all disconnect switches, all circuit breakers, all transformers, all current transformers, or building being in complete damage state	Failure of 80% of all circuits	Extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or building being in complete damage state

Table 3
HAZUS™ Component Damage-State Examples. This table lists substation names, probabilities that each one of the five different damage states will occur, and the Monte Carlo selected damage state for the Elysian Park earthquake scenario

Name	None	Slgt	Mod	Ext	Comp	Result
A	3%	4%	13%	64%	16%	Complete
Center	0%	0%	1%	36%	62%	Complete
F	1%	1%	4%	55%	39%	Complete
Mesa	1%	1%	3%	50%	46%	Complete
Rio Hondo	5%	15%	28%	47%	5%	Complete
Serrano	4%	7%	12%	70%	7%	Complete
B	3%	10%	21%	56%	10%	Extensive
Barre	3%	10%	21%	56%	10%	Extensive
Center	1%	3%	7%	53%	36%	Extensive
D	7%	18%	31%	41%	3%	Extensive
Del Amo	7%	18%	31%	41%	3%	Extensive
E	4%	7%	12%	70%	7%	Extensive
C	9%	22%	33%	34%	2%	Moderate
Cimgen	22%	36%	31%	11%	0%	Moderate
E	22%	36%	31%	11%	0%	Moderate
Eagle Rock	12%	15%	33%	39%	2%	Moderate
El Segundo	1%	18%	56%	20%	5%	Moderate
Ellis	9%	11%	28%	49%	4%	Moderate
Del Amo	5%	5%	18%	62%	11%	Slight
El Segundo	2%	24%	57%	15%	3%	Slight
Elizabeth Lake	72%	25%	3%	0%	0%	Slight
Estrero	90%	9%	0%	0%	0%	Slight
Q	12%	26%	35%	26%	1%	Slight
San Fernando	29%	40%	25%	6%	0%	Slight
Castaic	80%	19%	0%	0%	0%	None
Gould	29%	40%	25%	6%	0%	None
Rinaldi	50%	32%	17%	2%	0%	None
Santa Susana	90%	9%	0%	0%	0%	None
Santiago	54%	37%	9%	0%	0%	None
Santicoy	72%	25%	3%	0%	0%	None

Table 4.
Substations with Greatest Probability of Failure. Substations having probability of damage exceeding extreme greater than 50%, with the selected Monte Carlo damage state for the study scenario.

Name	Probability that Damage Exceeds Extensive	Result
P	100%	Ext
Center	98%	Comp
Laguna Bell	97%	Comp
Mesa	96%	Comp
F	94%	Comp
Coldgen	91%	Comp
Center	89%	Ext
Lighthipe	89%	Ext
Barre	89%	Ext
River	89%	Ext
Walnut	85%	Ext
Laguna Bell	84%	Ext
Refuse	80%	Comp
Growgen	80%	Comp
Mesa	80%	Ext
A	80%	Comp
Lewis	80%	Slgt
Rio Hondo	80%	None
E	77%	Ext
Serrano	77%	Comp
Pumpgen	76%	Ext
G	73%	Ext
Hinson	73%	Ext
Del Amo	73%	Slgt
B	66%	Ext
Barre	66%	Ext
Lighthipe	66%	Ext
Airway	64%	Comp
La Cienega	64%	Ext
La Fresa	64%	Mod
El Nido	64%	Ext
Arcogen	64%	Ext
Harborgen	64%	Comp
Olinda	64%	Ext
Villa Park	64%	Ext
Gramercy	59%	Mod
Hillgen	59%	Mod
Walnut	59%	Ext
H	53%	Ext
Johanna	53%	Ext
Goodrich	53%	Ext
Ellis	53%	Mod
Rio Hondo	52%	Comp

Table 5
Post-Earthquake Abnormal Voltages. WSCC control zones having post-earthquake substation voltages 10% or greater than normal, and number of substations with these abnormal voltages.

Control Zone	Number of Abnormal Voltages
Arizona	1
PG&E	14
Northwest	94
B.C. Hydro	4
W. Kootenay	1
Idaho	3
Montana	2
Sierra	3
PACE	3
WAPA L.M.	2
WAPA U.C.	1

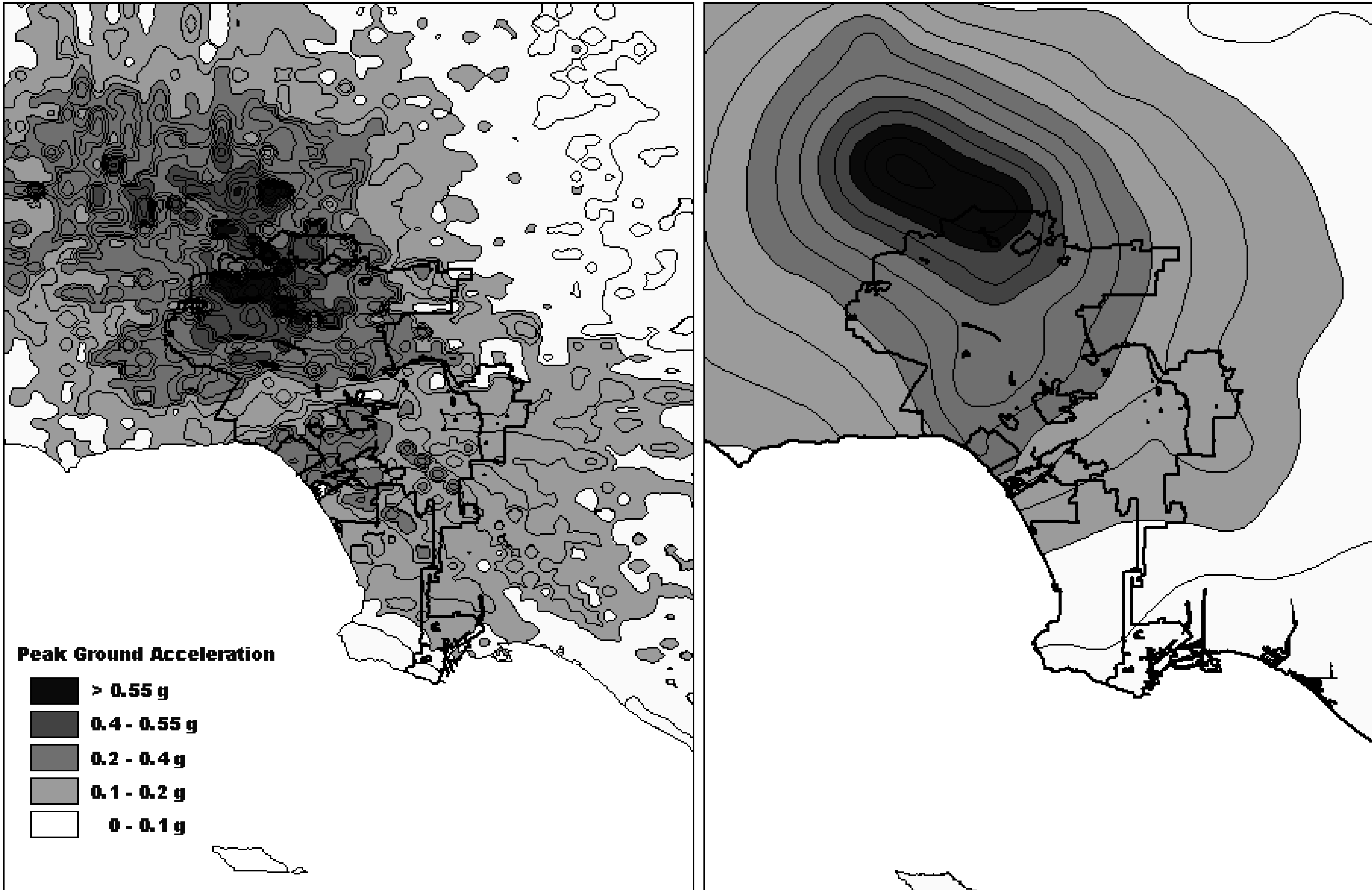


Figure 1.

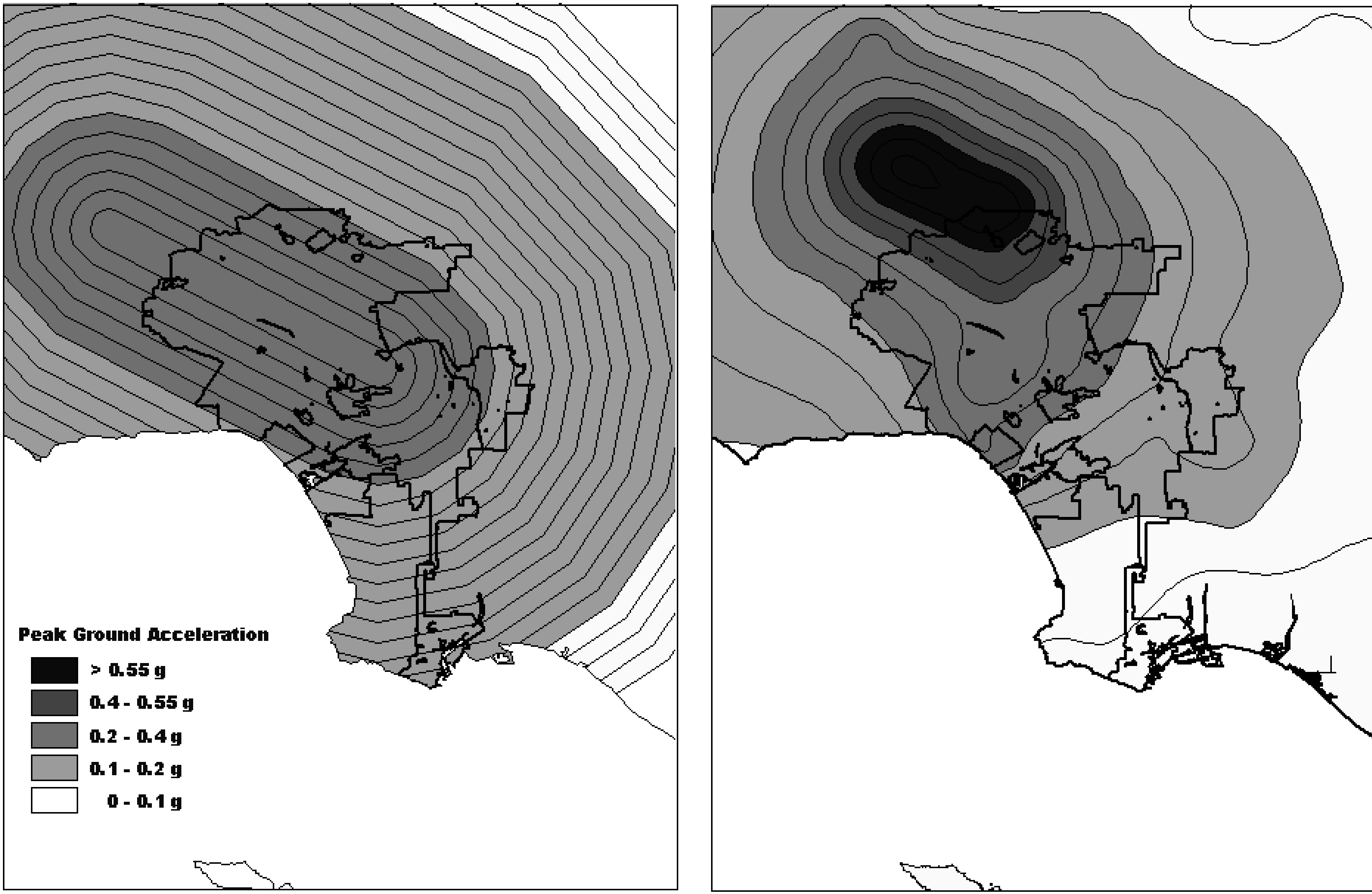
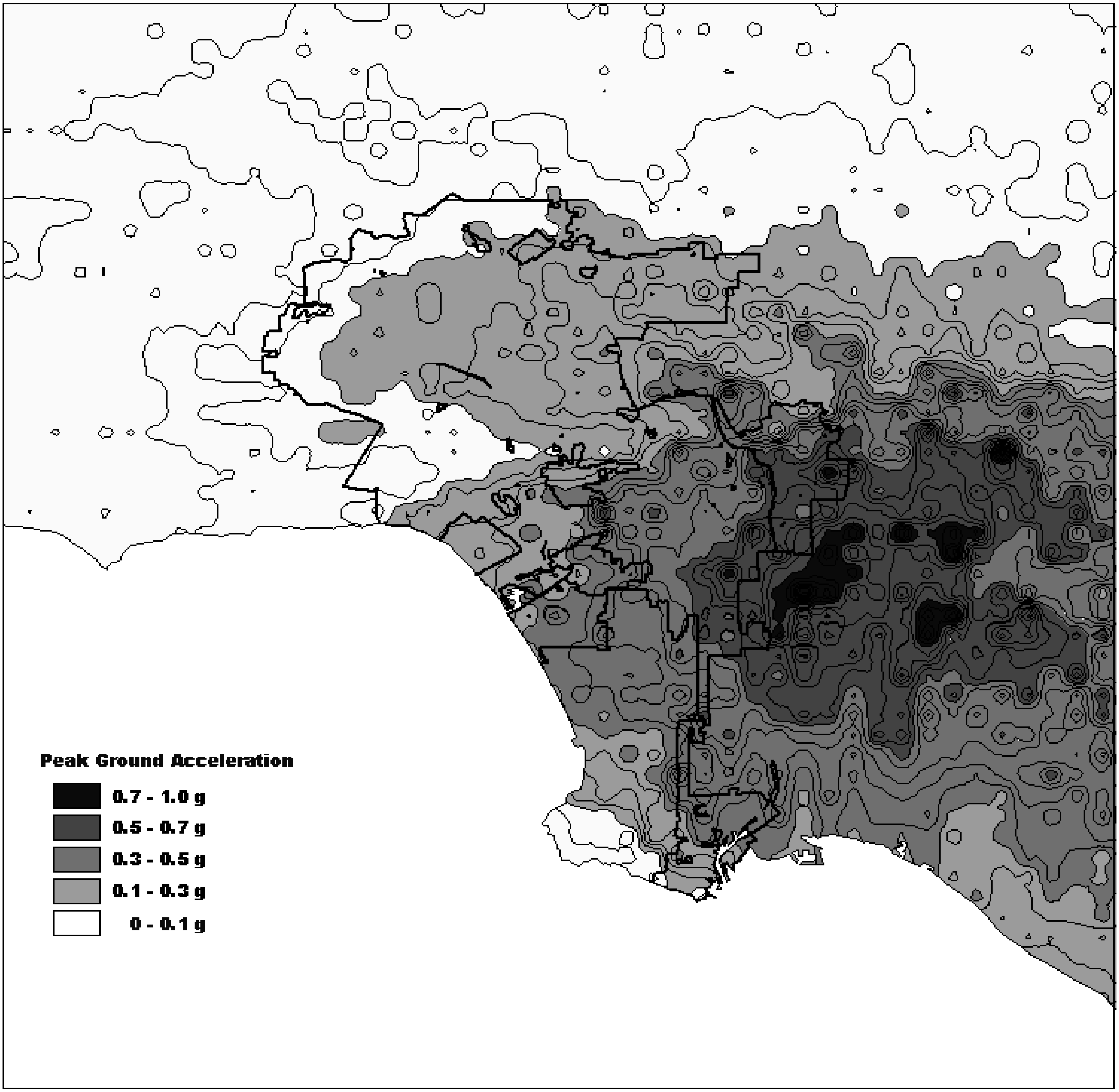


Figure 2.



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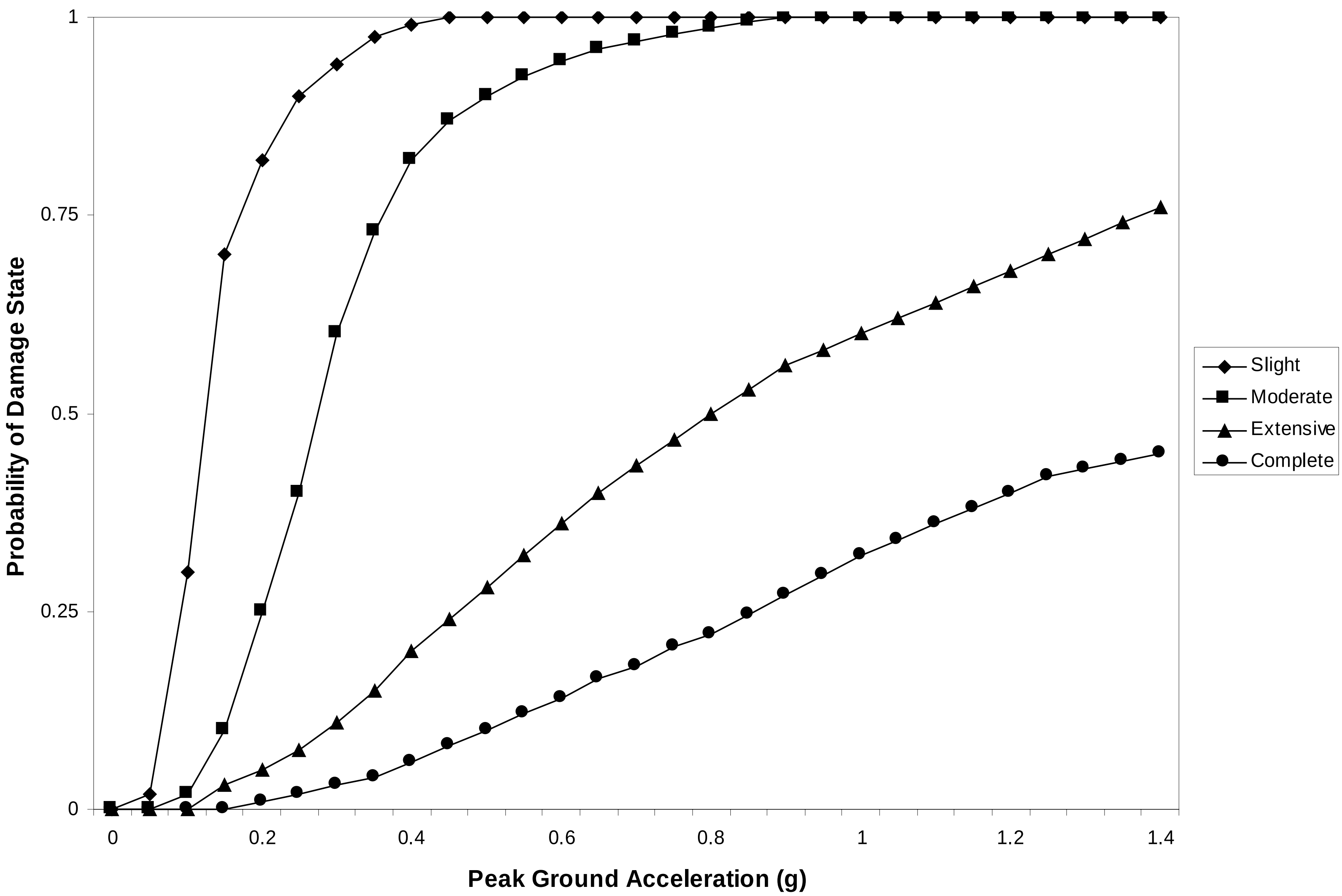


1
0.75
0.5
0.25
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Probability of Damage State
Peak Ground Acceleration (g)
Slight
Moderate
Extensive
Complete

Figure 4.

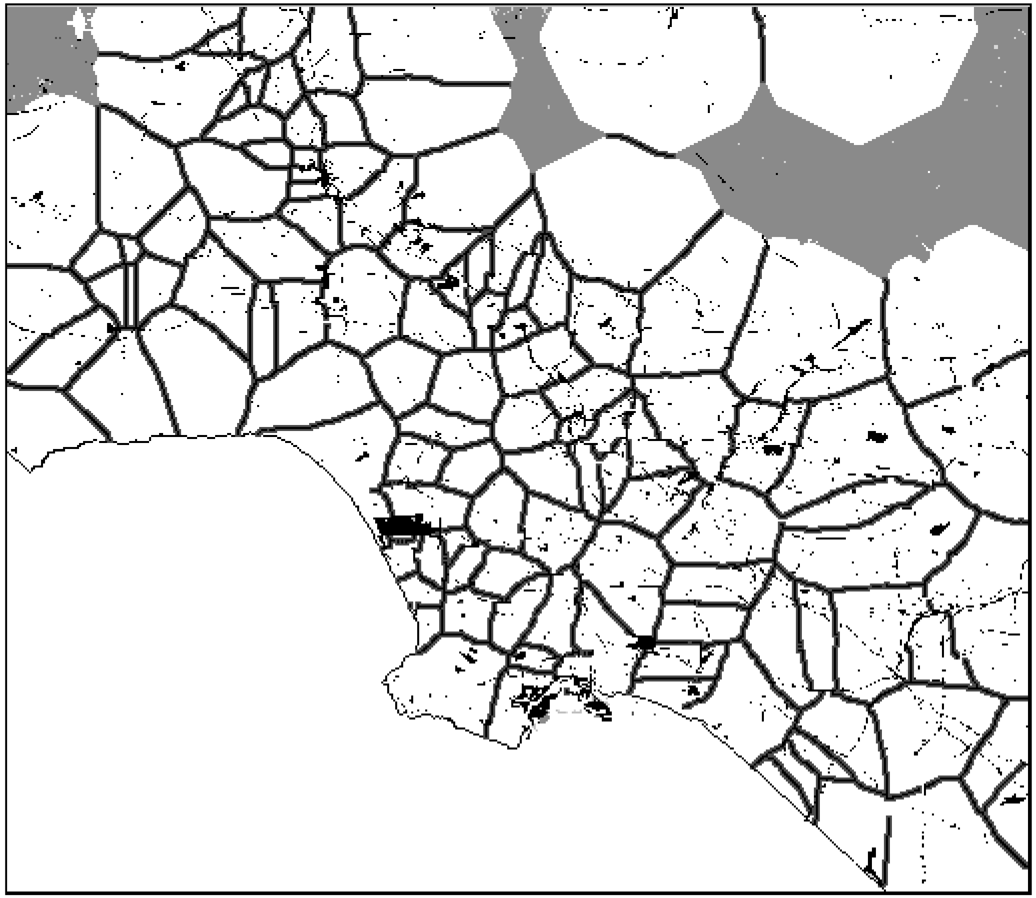
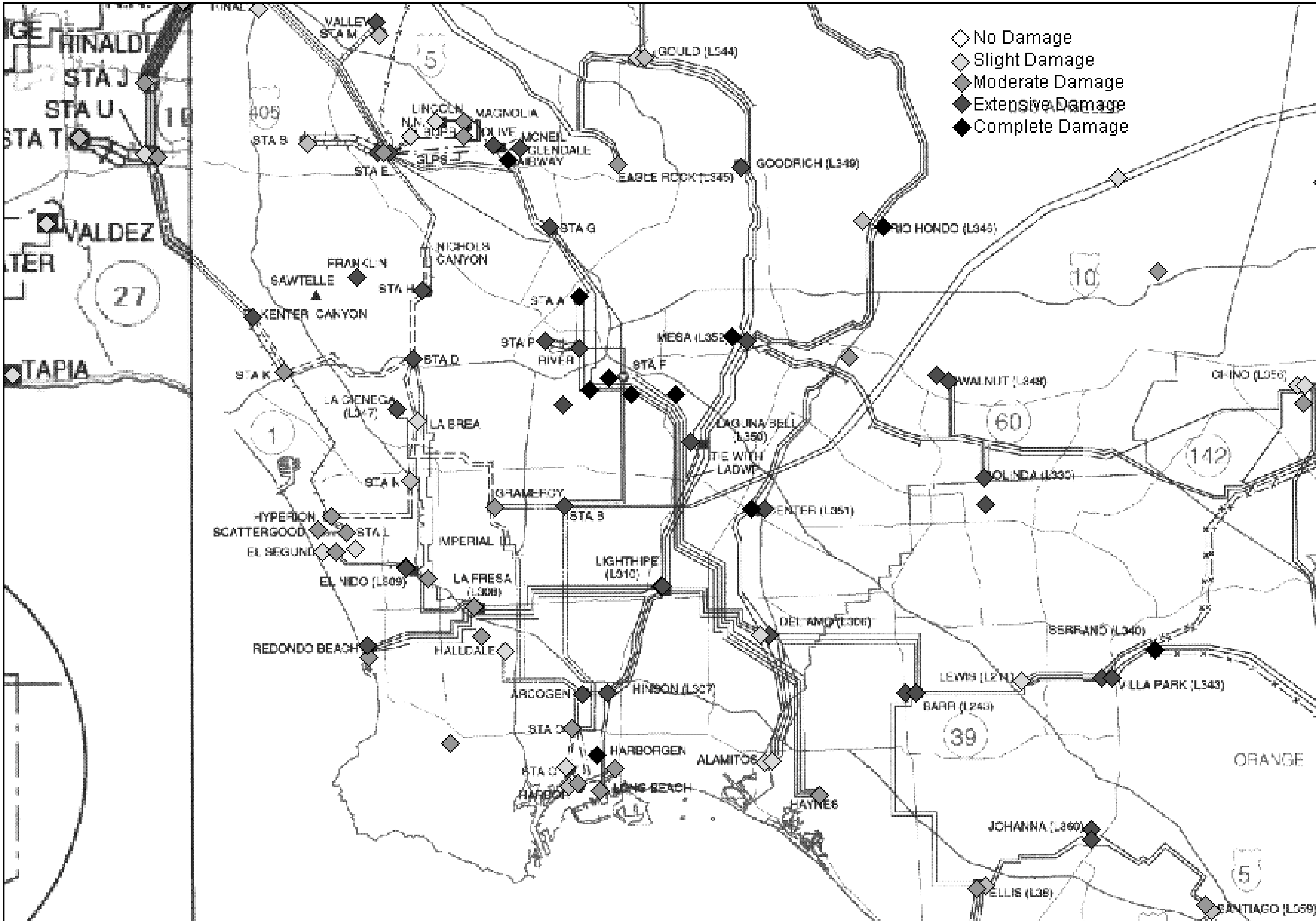


Figure 5.



No Damage
Slight Damage
Moderate Damage
Extensive Damage
Complete Damage
RINALDI
STA J
STA U
VALDEZ
TAPIA
VALLEY
STA M
GOULD (L344)
LINCOLN
MAGNOLIA
OLIVE
MCNEIL
GLENDALE
AIRWAY
STA B
STA E
EAGLE ROCK (L345)
GOODRICH (L349)
STA G
RIO HONDO (L346)
NICHOLS CANYON
FRANKLIN
SAWTELLE
STA H
KENTER CANYON
STA A
STA P
RIVER
MESA (L352)
STA F
STA D
STA K
WALNUT (L348)
CHINO (L356)
LA CIENEGA (L347)
LA BREA
LAGUNA BELL (L350)
TIE WITH LADWP
OLINDA (L330)
GRAMERCY
STA B
CENTER (L351)
HYPERION
SCATTERGOOD
STA L
EL SEGUNDO
IMPERIAL
LIGHTHIPE (L310)
EL NIDO (L309)
LA FRESA (L308)
DEL AMO (L306)
SERRANO (L340)
REDONDO BEACH
HALLDALE
LEWIS (L211)
VILLA PARK (L343)
BARR (L243)
ARCOGEN
HINSON (L307)
STA C
HARBORGEN
ALAMITOS
LONG BEACH
HAYNES
ORANGE
JOHANNA (L360)
ELLIS (L38)
SANTIAGO (L359)
5
405
10
27
1
60
142
39

Figure 6.

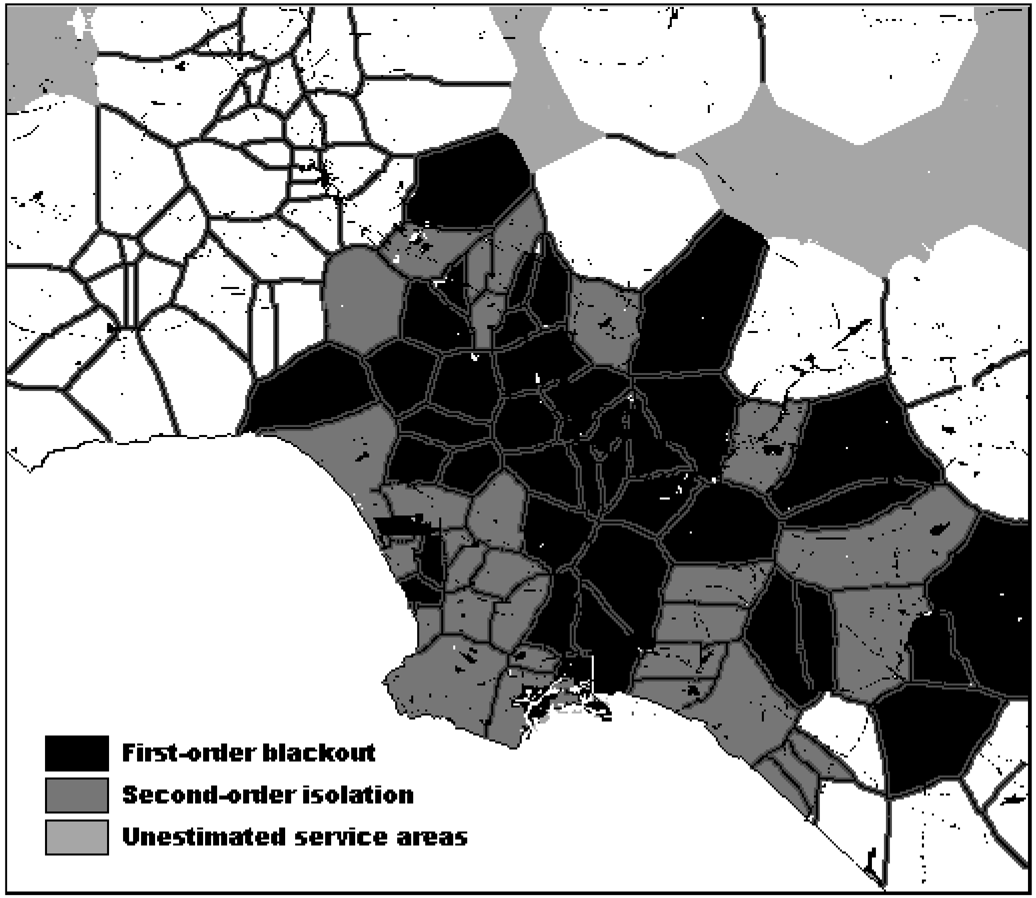

First-order blackout
Second-order isolation
Unestimated service areas

Figure 7.

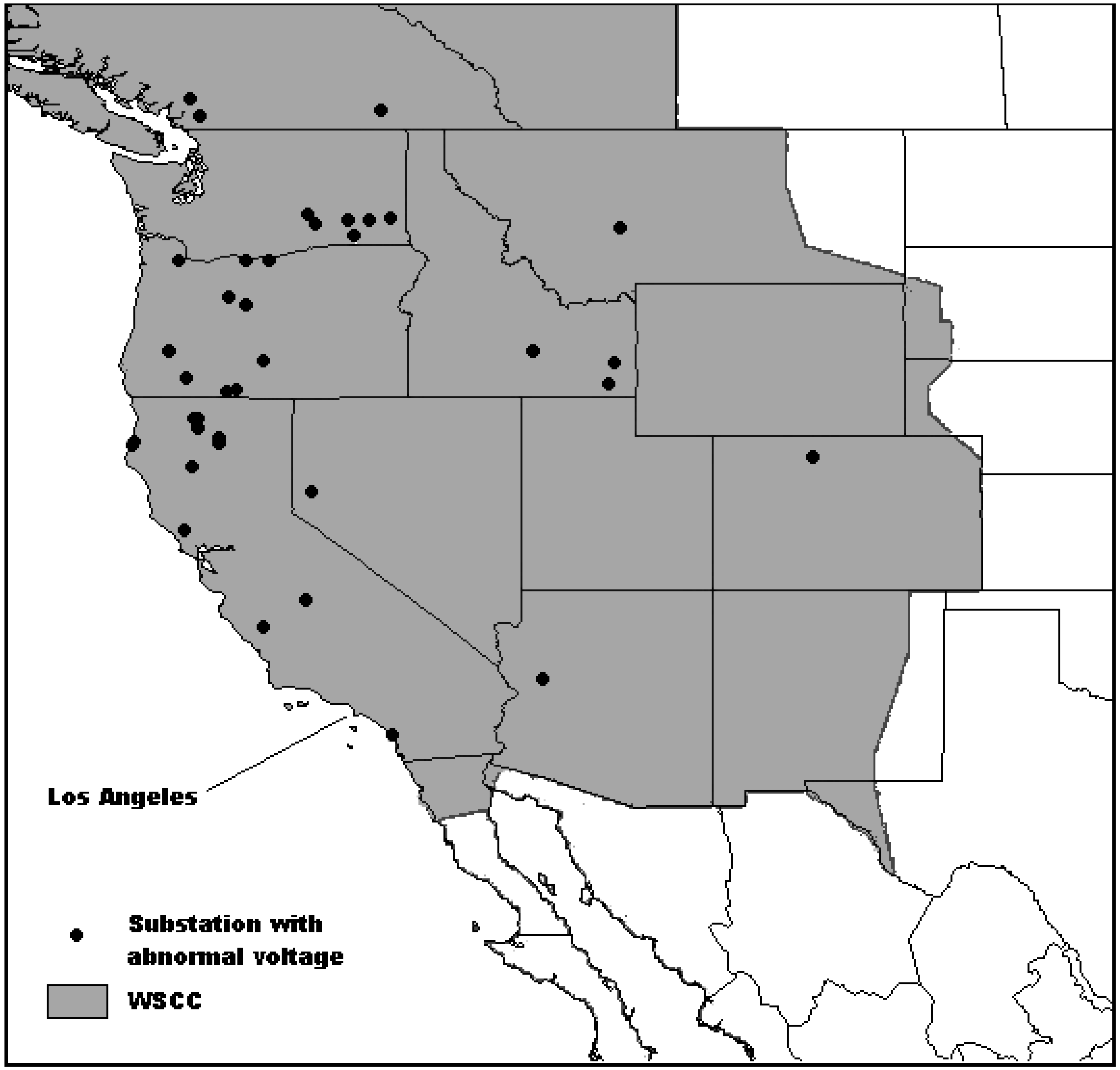


Figure 8.